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## Movement characteristics of upper extremity prostheses during basic goal-directed tasks

Hanneke Bouwsema<sup>a,\*</sup>, Corry K. van der Sluis<sup>b</sup>, Raoul M. Bongers<sup>a</sup>

<sup>a</sup> Center of Human Movement Sciences, University of Groningen, Groningen, The Netherlands

<sup>b</sup> Center for Rehabilitation, University Medical Center Groningen, Groningen, The Netherlands

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### ABSTRACT

**Background:** After an upper limb amputation a prosthesis is often used to restore the functionality. However, the frequency of prostheses use is generally low. Movement kinematics of prostheses use might suggest origins of this low use. The aim of this study was to reveal movement patterns of prostheses during basic goal-directed actions in upper limb prosthetic users and to compare this with existing knowledge of able-bodied performance during these actions.

**Methods:** Movements from six users of upper extremity prostheses were analyzed, three participants with a hybrid upper arm prosthesis, and three participants with a myoelectric forearm prosthesis. Two grasping tasks and a reciprocal pointing task were investigated during a single lab session. Analyses were carried out on the kinematics of the tasks.

**Findings:** When grasping, movements with both prostheses showed asymmetric velocity profiles of the reach and had a plateau in the aperture profiles. Reach and grasp were decoupled. Kinematics with the prostheses differed in that the use of upper arm prostheses required more time to execute the movements, while the movements were less smooth, more asymmetric, and showed more decoupling between reach and grasp. The pointing task showed for both prostheses less harmonic movements with higher task difficulty.

**Interpretation:** Characterizing prosthetic movement patterns revealed specific features of prosthetic performance. Developments in technology and rehabilitation should focus on these issues to improve prosthetic use, in particular on improving motor characteristics and the control of the elbow, and learning to coordinate the reach and the grasp component in prehension.

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### 1. Introduction

When one loses part(s) of an upper extremity, a lot of functions of the arm, such as reaching out and manipulating objects, are lost. To restore these functionalities, an upper extremity prosthesis is often used to replace the arm. Although a prosthesis replaces most basic activities of the missing arm it obviously differs from the sound arm and hand. For instance, the human hand has many degrees of freedom of movement and a very complex sensory system, whereas the prosthetic hand is constrained to only one or a few degrees of freedom of movements and it provides very limited sensory feedback. The challenge for the prosthetic user is to perform actions given these limitations in a dexterous way.

The use of a prosthesis is often studied by means of questionnaires (e.g. Gaine et al., 1997; Pezzin et al., 2004; Silcox et al., 1993; Wright et al., 1995). However, the way amputees actually handle their

prosthesis in basic activities of the upper limb, such as pointing to a target or grasping an object, has received only very little attention. This lack of studies concerning prosthetic movements stands in sharp contrast to the numerous studies into pointing and prehension of sound arms and hands (e.g., Jeannerod, 1981, 1984, 1995; Marteniuk et al., 1990; Zaal et al., 1998). Describing the differences between movements made with prosthetic devices and sound hands might contribute to our comprehension of motor control processes underlying movements with prostheses. These insights could advance the design of upper extremity prostheses and training programs to use these devices. Our aim therefore is to characterize movement patterns of the prosthetic arm and hand during pointing and grasping and to compare these patterns with existing knowledge of able-bodied movement patterns.

Both pointing and grasping in able-bodied participants are well-studied tasks (e.g., Fitts, 1954; Jeannerod, 1981, 1984, 1995; Marteniuk et al., 1990; Zaal et al., 1998). Sound prehension is characterized by a bell-shaped velocity profile of the reach. During the reach, the hand gradually opens until a maximum aperture is reached at approximately two third of the reach, after which the hand closes around the object. The start of the reach and the grasp and their end-

\* Corresponding author. Center for Human Movement Sciences, University of Groningen, P.O. Box 196, NL-9700 AD Groningen, The Netherlands.

E-mail address: [H.Bouwsema@rug.nl](mailto:H.Bouwsema@rug.nl) (H. Bouwsema).

point are tightly coupled (Jeannerod, 1981, 1984). Pointing movements are also characterized by a bell-shaped velocity profile. The performance of these movements is often described with the use of Fitt's law (Fitts, 1954), which describes how movement speed is related to accuracy requirements. Movements with a higher index of difficulty (ID, i.e., smaller targets further away) have longer movement times. The velocity profile changes over task difficulty where a higher ID gives rise to a longer deceleration phase.

Studies concerning movements with prostheses mostly focused on body movements in tasks of daily living (Carey et al., 2008; Carey et al., 2009; Highsmith et al., 2007; Popat et al., 1993). Although these studies provide insight into the actual use of prostheses they did not address prehensile patterns or end-point accuracy, therefore, performance with prostheses cannot be compared to existing knowledge of able-bodied performance in reaching and grasping.

Doeringer and Hogan (1995) compared performance of both arms of unilateral above elbow amputees using a body-powered prosthesis in a regular pointing, a blind pointing and a tracking task, in which the elbow angle was connected to a target cursor position. They showed that end-point accuracy was comparable between the arms but that more movements with the prosthesis were required to meet the demands of these tasks. Schabowsky et al. (2008) compared reaching performance in a novel force-field environment between below elbow amputees using a body-powered prosthesis and able-bodied participants. Early in learning performance was practically similar in both groups while late in learning error was larger in the prosthetic group. Prehension was studied by Fraser and Wing (Fraser and Wing, 1981; Wing and Fraser, 1983) and Wallace et al. (2000). Only Fraser and Wing reported prehensile patterns and end-point kinematics. They studied one body-powered forearm prosthetic user, and found some distinctive characteristics in the prehensile pattern of the prosthesis. Movement times were longer, hand closure was delayed compared to the sound hand, and the hand showed a plateau in the aperture profile instead of a single peak.

In this study, we characterize movement patterns of prosthetic arms during grasping and pointing movements—using a Fitts' task—and we compare these patterns to known characteristics of sound movements. To reveal the effect of properties of the prosthesis on performance, we evaluate both forearm and upper arm prosthetic users. In prehension, we expect to find a plateau in the hand aperture, as found by Fraser and Wing (Fraser and Wing, 1981; Wing and Fraser, 1983), and a decoupling between reach and grasp, especially with the upper arm prostheses due to the mechanical elbow in these prostheses. Positioning and controlling the prosthetic hand while also controlling the prosthetic elbow might be difficult with upper arm prostheses. In the pointing task, we expect that, although Fitts' task has never been used in upper limb prostheses before, Fitts' law should be found in prosthetic pointing movements, since literature has shown that the law applies to many situations (Plamondon and Alimi, 1997), including body extensions (Baird et al., 2002). Moreover, we used a rhythmic pointing task because it allowed us to characterize the underlying motor control processes.

## 2. Methods

### 2.1. Participants

We recruited participants by sending letters to customers of an orthopedic workshop and by placing information on the website of the Dutch national association of amputated persons (the Landelijke Vereniging van Geamputeerden, LVVG). Fifteen people responded. Eight of those were included in the study, all with an acquired amputation, and they satisfied the following criteria: (1) free of neurological or motor problems; (2) normal or corrected to normal sight; (3) daily use of the prostheses, for at least 8 hours a day. Two participants were excluded from further analyses. They could not

complete the experiment due to fatigue and technical difficulties. Characteristics of the remaining six participants are presented in Table 1. The forearm amputees used myoelectric prostheses; contracting muscles produce myoelectric signals that are picked up at the surface of the skin by sensors built into the socket of the prosthesis to control the motor in the hand. The upper arm amputees used hybrid prostheses, a combination of a myoelectric hand coupled with a mechanical elbow. The elbow functioned by manipulating tension on a cable connected to a harness system fitted around the contralateral shoulder. All participants used Digital Twin® hands (Otto Bock). The study was approved by the Medical Ethics Committee of the University Medical Center Groningen, and the participants gave their informed consent prior to participation.

### 2.2. Tasks

Three different tasks were examined. In the direct grasping task, participants reached out for and grasped an object positioned on the table in front of them with their prosthetic hand. In the indirect grasping task, participants handed an object over from their sound hand to the prosthetic hand. In the pointing task, participants made horizontal back and forth movements between two vertical bars, with a stylus held in their prosthetic hand.

### 2.3. Apparatus

The positions of both the sound hand and the prosthetic hand were measured using an OPTOTRAK 3020 system (Northern Digital, Waterloo, Canada) recording from above the table. The positions of seven infrared light emitting diodes (LEDs) were sampled with a frequency of 100 Hz. One LED was placed on the ulnar border of the thumb-nail, one along the radial border of the nail of the index finger, and one was placed on the styloid process of the radius of the sound hand. Three LEDs were placed on corresponding positions of the prosthetic hand. The other LED was placed on the object.

For the direct grasping task the initial hand position of the prosthesis was located 15 cm from the edge of the table, in line with the shoulder. The object could be placed at 20, 30, and 40 cm from the initial hand position in line with the shoulder. For the indirect grasping task, the initial positions of the sound and prosthetic hand were 25 cm from the edge of the table, with three distances (20, 30 and 40 cm) between both hands. The object was situated in the sound hand. The midpoint between the two hands was aligned with the body midline. Three wooden cylinders with a height of 10 cm and a diameter of 2, 4, and 6 cm were used in the grasping tasks.

In the pointing task, movements were made with a nonmarking stylus held in the prosthetic hand, on a Wacom Graphics digitizing tablet, connected to a computer running the program OASIS. This provided two-dimensional position coordinates of the pen at a rate of 170 Hz. The targets were printed on laminated A3 sheets, which were attached to the digitizing tablet in landscape orientation.

### 2.4. Experimental design

In a single lab session, the three tasks were presented in separate blocks with the order balanced over participants. For both grasping tasks, the three objects and the three object distances were presented in randomized blocks. The participants had to grasp 45 times in each of the two tasks.

The targets used in the pointing task varied in distance (5, 10, 20, and 30 cm) and index of difficulty (ID) (3, 4, and 5; computed as  $ID = \log_2(2 \times \text{target distance} / \text{target size})$ ; Fitts, 1954). This resulted in 12 conditions, with target sizes varying from 0.31 cm to 7.50 cm in width. These conditions were presented in random order.

**Table 1**  
Characteristics of the participants.

Sex	Male	Male	Male	Female	Female	Female
Age	56	49	41	37	60	30
Level of amputation	Upper arm	Upper arm	Upper arm	Fore arm	Fore arm	Fore arm
Type of prosthesis	Hybrid	Hybrid	Hybrid	Myoelectric	Myoelectric	Myoelectric
Years of prosthetic use	20	34	7	1	8	12
Years of usage of present type of prosthesis	4	3	2	1	8	12
Affected side	Right	Right	Right	Right	Left	Left
Hand dominance	Right	Right	Right	Right	Right	Right

## 2.5. Procedure

The participants were seated at a table and commenced with their prosthetic hand closed. For the direct grasping task the participants were instructed to grasp the object with their prosthetic hand and lift it up approximately 5 cm. In the indirect grasping task the participants were instructed to hand over the object from the sound hand to the prosthetic hand, using movement of both hands. No further instructions about the movements of each hand were given.

In the pointing task, the participants performed 40 horizontal back and forth movements with the stylus between two vertical bars printed on a model sheet. Before the start of each movement, the stylus had to be placed on one of the bars. The instruction was to move as rapidly as possible, but keeping errors under 20%. If the participant produced more than two consecutive trials with either zero or too many errors, the participant was told to adjust speed and the trial was rerun. The trial was also rerun if the pen left the tablet. The error rate of 20% was chosen because in the difficult trials, it was hard for the participants to achieve the normally used error rate of 5% (Langolf et al., 1976; Mottet and Bootsma, 1999), although a conventional range of IDs was used.

## 2.6. Data analysis

High frequency noise was removed from the position data of the OPTOTRAK LEDs and of the digitizing pen using a second order recursive Butterworth filter with a cut-off frequency of 10 Hz. The position signals were differentiated twice with a 3-point difference algorithm, once to acquire the velocity and again for the acceleration. Trials in which markers were invisible were rejected.

## 2.7. Grasping tasks

The reach was defined as the average of the positions of the LEDs on the index finger and the thumb of the prosthetic hand. For the grasping tasks, the onset and termination of the reach were determined by a 5 cm/s threshold. The time from reach onset until reach termination was the movement reach time; peak velocity was also determined. For both tasks these measures were computed relative to the position of the object—note that the object moved in the indirect grasping task. The grasp was defined by the distance between the LEDs on the thumb and index finger, and maximum hand aperture was determined. The time between grasp onset and grasp termination (determined by a threshold of 2 cm/s) defined movement grasp time. The period from the end of finger opening and the start of finger closure—also determined by a threshold of 2 cm/s—was defined as duration of the plateau phase. We computed onset asynchrony by subtracting the time of grasp onset from the time of reach onset, and termination asynchrony by subtracting the time of grasp termination from the time of reach termination.

## 2.8. Pointing task

The extremes in position defined half cycles. We used half cycles 10 to 35 for analyses. Movement time and peak velocity were

averaged over these 25 half cycles. Graphical analyses were done on Hooke portraits (acceleration versus position). In a fully harmonic, rhythmic movement, the Hooke portrait shows a straight line with a negative slope. When the movement is a concatenation of discrete movements—a full stop at the reversal points—the movement of each half cycle ends with a complete deceleration until zero; the Hooke portrait becomes N-shaped. To analyze the harmonic nature of the movements we used a measure of movement harmonicity ( $H$ ) developed by Guiard (1993, 1997), where  $H = 1$  means a complete harmonic motion, and  $H = 0$  means a pure concatenation of movements (Buchanan et al., 2003; Guiard 1993, 1997). A small  $H$  indicates that more control is exerted around the targets.

## 2.9. Statistical analysis

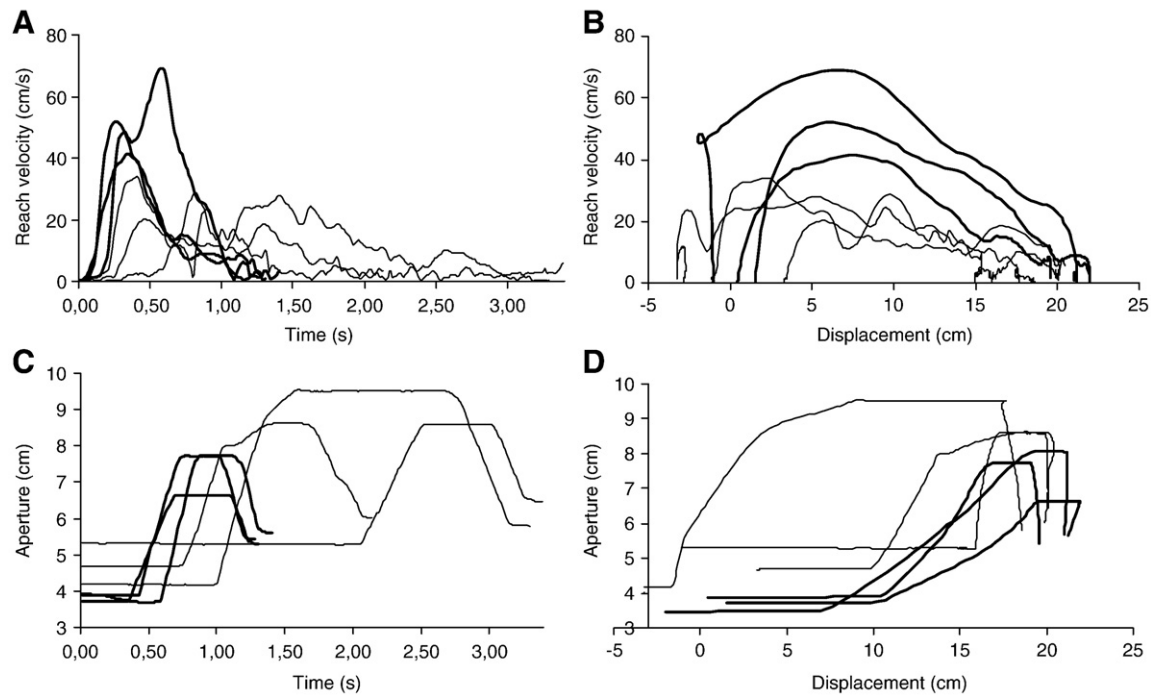
Repeated measures ANOVAs were carried out in the grasping tasks with object size (2, 4, and 6 cm), object distance (20, 30, and 40 cm) and task (direct and indirect) as within-subject factors and prosthesis (forearm versus upper arm) as between-subject factor. In the pointing task index of difficulty (3, 4, and 5) and target distance (5, 10, 20, and 30 cm) were used as within-subject factors and prosthesis (forearm versus upper arm) as between-subject factor. When Mauchly's sphericity was violated, the degrees of freedom were adjusted with the Greenhouse–Geisser correction. In all analyses an  $\alpha$  of .05 was used, and post hoc tests on main effects used Bonferroni corrections. Generalized eta-squared (Bakeman 2005) was used to calculate effect sizes, and interpreted according to Cohen's recommendation (1988) of .02 for a small effect, .13 for a medium effect, and .26 for a large effect. Only the effects with an effect size larger than .02 are discussed in the results.

## 3. Results

### 3.1. Grasping

In the grasping tasks, 493 trials out of the 540 were analyzed. Fig. 1 presents typical examples of hand velocity and hand aperture as a function of time and displacement for both types of prostheses in the direct grasping task. The velocity profiles (see Fig. 1A and B) were asymmetrical; the acceleration phase was relatively short compared to the deceleration phase. The upper arm prostheses had shorter movement times and trajectories were less smooth than those of the forearm prostheses. All prostheses showed a plateau in the aperture profile (Fig. 1C and D). Due to the characteristics of the motor of the hand, velocity of hand opening and hand closing was constant and was almost instantly reached. Overall, hand opening started much later than the reach, and the hand did not close until the end of the reach, that is, when the hand was already around the object (Fig. 1D).

The 3D-trajectories of the finger and thumb (Fig. 2) were smooth trajectories for the forearm prostheses, whereas those trajectories of the upper arm prostheses were interrupted at the moment the elbow was uncoupled in order to direct the hand towards the object.



**Fig. 1.** Reach velocity profiles (upper row) and aperture profiles (lower row) of the forearm prostheses (bold lines) and the upper arm prostheses (thin lines) for each participant, plotted for the direct grasping task with an object of 2 cm at a distance of 20 cm. The reach velocity and aperture are plotted against time on the left, and against displacement on the right. Velocity and aperture are aligned. Note that one of the participants started the movement before 0, at approximately  $-3$  cm (B and D), but still moves 20 cm, therefore it appears as if he ends the movement earlier.

### 3.2. Movement reach time

The upper arm prostheses required more time to execute the reach than the forearm prostheses (see Table 2). The movement reach time was weakly influenced by object distance. The direct grasping task had significantly longer reach times than the indirect grasping task.

### 3.3. Peak velocity

Peak velocity of the reach was larger for larger object distances. Post hoc analyses showed that all object distances were significantly different (all  $P$ 's  $\leq .01$ ). Peak velocity was higher in the direct grasping task compared to the indirect grasping task. Although not significant, forearm prostheses had higher peak velocities (59 cm/s, sd 15) than the upper arm prostheses (33 cm/s, sd 11).

### 3.4. Movement grasp time

Grasp time was significantly longer for the upper arm prostheses (Table 2). Furthermore, with large objects the movement grasp time was slightly longer than with small objects.

### 3.5. Plateau time

The plateau in the aperture profile had a mean duration of 813 ms (sd 701) for the upper arm prostheses, and 234 ms (sd 183) for the forearm prostheses. However, this difference was not significant, probably due to the large variation in plateau time within the upper arm prostheses.

### 3.6. Maximum hand aperture

Maximal hand aperture was larger for larger objects. Post hoc pairwise comparisons showed that all the objects differed significantly from each other.

### 3.7. Onset and termination asynchrony

The asynchrony between the start of the hand opening and the start of the reach was on average 351 ms for the upper arm prostheses, and 254 ms for the forearm prostheses, but this difference was not significant. Hand closing ended much faster after the end of the reach for the forearm prostheses than for the upper arm prostheses (Table 2).

### 3.8. Pointing

Five of the 72 trials of the pointing task were lost as the cable of the prosthesis of one of the participants broke during the experiment. Fig. 3 presents the movement trajectories in the pointing task in the form of Hooke portraits (position versus acceleration). For the lowest ID (ID = 3), the almost straight line indicated an almost harmonic movement. With larger IDs the Hooke portrait became N-shaped, indicating that the movement became less harmonic. This was the case for both types of prostheses.

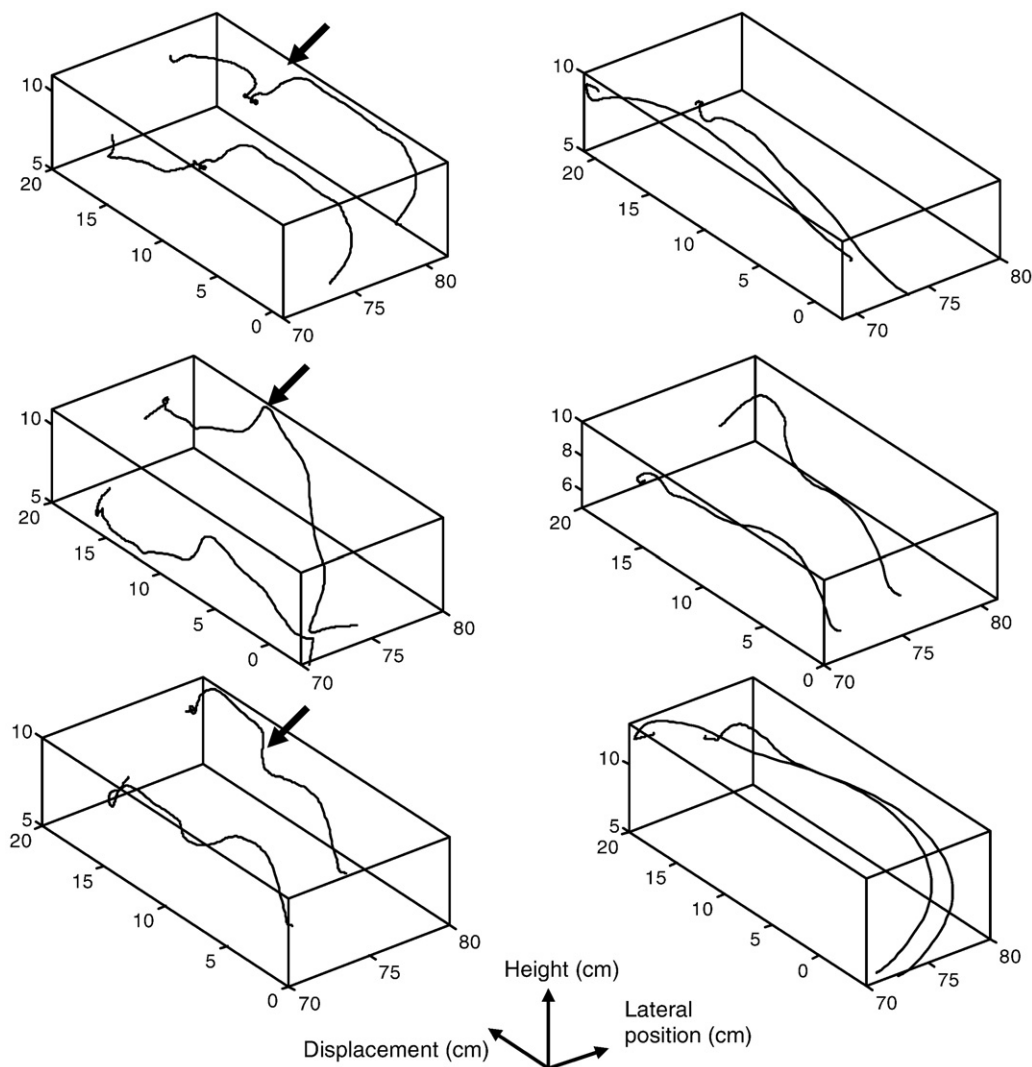
### 3.9. Movement time

The ANOVA showed that a higher ID resulted in longer movement times ( $F(2,4) = 16.34$ ,  $P = .01$ ;  $\eta^2_G = .46$ ; see Table 3 for means and sd). Pairwise comparisons revealed that the ID differed significantly between 4 and 5 ( $P = .01$ ). MT and ID were linearly related,  $MT = -.13 + .19 \cdot ID$  ( $F(1,64) = 52.41$ ,  $P = .00$ ;  $R^2 = .45$ ).

### 3.10. Harmonicity

A higher ID resulted in a lower index of harmonicity ( $F(2,4) = 22.564$ ,  $P = .007$ ;  $\eta^2_G = .51$ ), as indicated by the N-shaped Hooke portrait with a higher ID. Pairwise comparisons revealed that ID 3 and 5 differed significantly from each other ( $P = .01$ ).





**Fig. 2.** 3D plots of the trajectory of the upper arm prostheses (left) and the forearm prostheses (right) for each participant, in the direct grasping task with an object of 2 cm at a distance of 20 cm. The uncoupling of the elbow in the upper arm prostheses is indicated by the arrows.

## 4. Discussion

### 4.1. Movement patterns with prostheses

In prehension, reach velocity profiles were asymmetric in all prostheses, with a short acceleration phase and a long deceleration phase. As expected, based on the studies of Fraser and Wing (Fraser and Wing, 1981; Wing and Fraser, 1983), in prehension the grasp ended later than the reach implicating uncoupling of the reach and the grasp, while the aperture profile showed a plateau. In the pointing task, a higher task difficulty gave rise to longer movement times and a decrease in harmonicity, indicating that Fitts' law applies to prosthetic movements too.

### 4.2. Prosthetic versus able-bodied performance

Prehension with the prostheses was characterized by long movement times, uncoupling of the reach and grasp and, most noticeable, a plateau in the aperture profile. All three characteristics are generally not reported in able-bodied prehension. These differences may originate from several aspects, of which we present two here. First, because of the lack of proprioceptive feedback, prosthetic users must rely primarily on vision (cf. Fraser and Wing, 1981; Wing and Fraser, 1983). Visual feedback is slower than proprioceptive

feedback, which results in slower movement speed and, in addition, presumably affects the control of hand closing in particular, resulting in a plateau phase and the uncoupling of reach and grasp. Second, due to mechanical properties of the motor of the prosthetic hand, opening and closing had a constant velocity that was almost instantly reached at the start of hand opening and hand closing. If hand closure were to start immediately after maximum aperture, as in sound grasping, the hand would close too early, before the hand would actually enclose the target. Keeping the hand open at a plateau would prevent this from happening. It would be interesting to study whether the plateau still exists in recent available prosthetic hands with proportional speed control.

The decrease of harmonicity and the longer movement times with higher IDs in the pointing task, are in agreement with what is usually found in able-bodied performance (cf. Mottet and Bootsma, 1999). The shape of the non-harmonic movements of the prostheses in the high ID task indicated that more control is exerted around the targets. Since this is also the case for able-bodied performance, this might suggest that in pointing the prostheses are controlled as a sound hand. However, the movement times of the prostheses were almost twice as long with the same IDs (Fitts 1954; Langolf et al., 1976). Longer movement times were also found by Baird et al. (2002) who studied a Fitts' task in probe usage. Probes, like prostheses, are an extension to the body. However, the movement times in our study were much

**Table 2**  
Mean (SD), F, P and  $\eta^2_G$  for the significant effects.

Dependent variable	Within-/between subject factor		Mean (SD)	F	P	$\eta^2_G$
Movement reach time (ms)	Prosthesis	Forearm	1003 (311)	10.16	.03	.47
		Upper arm	1569 (607)			
	Object distance	20	1199 (430)	5.45	.03	.02
		30	1277 (412)			
Movement grasp time (ms)	Prosthesis	Forearm	1465 (344)	8.91	.04	.23
		Upper arm	1086 (508)			
	Object size	2	965 (216)	13.67	.02	.58
		4	1840 (833)			
Peak velocity (cm/s)	Prosthesis	Forearm	1306 (470)	13.87	.00	.02
		Upper arm	1338 (424)			
	Object distance	20	1528 (455)	36.76 (9.9)	93.59	.00
		30	47.39 (10.54)			
Maximal hand aperture (cm)	Prosthesis	Forearm	54.37 (12.29)	51.72 (67.94)	10.18	.03
		Upper arm	39.97 (11.83)			
	Object size	2	7.71 (1.13)	19.08	.00	.49
		4	8.52 (0.99)			
Termination asynchrony (ms)	Prosthesis	Forearm	9.39 (1.06)	61 (.13)	9.53	.04
		Upper arm	477 (.62)			

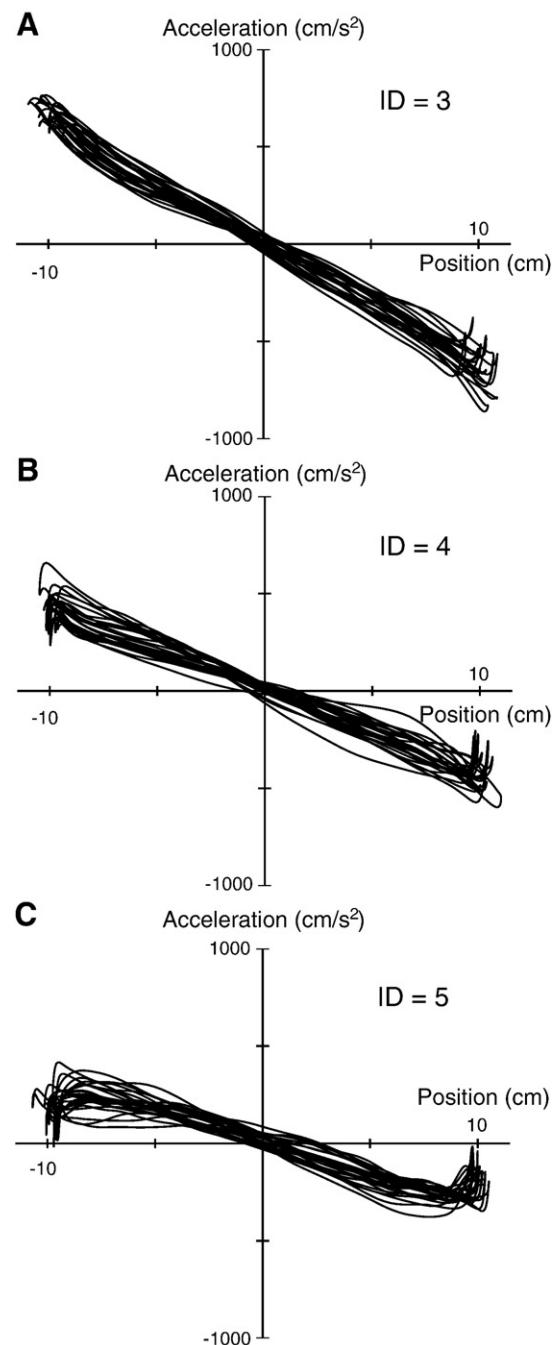
longer than Baird et al. (2002) found. Moreover, in our study, it was not just the increased arm length that influenced performance, since there was no difference in movement time between the two types of prostheses, which differed considerably in length. It seemed that characteristics of the prostheses other than length made the task more difficult to execute, resulting in longer movement times and higher levels of error rate (Langolf et al., 1976; Mottet and Bootsma, 1999).

#### 4.3. Differences between the two types of prostheses

The movement trajectories of the upper arm prostheses were less smooth compared to the forearm prostheses, and the movement times were longer in the grasping tasks. As expected, the reach velocity profile was more asymmetric and the reach and the grasp were more decoupled in the upper arm prostheses, probably due to properties of the mechanical elbow. Furthermore, because upper arm muscles tend to co-contract (Rahadkrisnan et al., 2008), it may be harder to control opening or closing the prosthetic hand correctly, as at the same time the muscles are also needed for the reach action. This suggests that using—and learning to use—an upper arm prosthesis might be more difficult than using a forearm prosthesis.

#### 4.4. Future research

The characteristics of prosthetic behavior demonstrated in the present study might guide future research to increase prosthetic use. Prosthetic use can be defined in two ways: by the technical possibilities offered by a prosthesis, and by the functionality, the way an amputee handles the prosthesis (Bouwsema et al., 2008). Our findings reveal that the function of the prosthetic hand with constant speed, does not resemble natural hand aperture, and, thus, might be disturbing for the user. Prosthetic hands with gradual hand opening might be easier to use because they allow a closer replication of able-bodied grasping. Moreover, it is advised to improve elbow control-systems and to improve myoelectric control schemes of the prosthetic hand so that they are less sensitive for co-contractions, something that now hinders the use of upper arm prostheses. The current results also point to aspects that should be attended to prosthetic training in



**Fig. 3.** Hooke portraits: acceleration versus position for the three different IDs (ID3 (A), ID4 (B) and ID 5 (C)) at a target distance of 20 cm.

order to enhance the prosthetics' functionality, such as learning to coordinate the reach and grasp component.

#### 4.5. Study limitations

The study had a few limitations. We had only a small group of participants, and therefore, generalizability of our study is low. Another limitation of the study was co-occurrence in our participant group with the hand dominance and the type of prosthesis used. As Carey et al. (2008) stated that previously dominant side does not exert much influence, we do not expect that this influenced our results. An important aspect to note is that we observed the most ideal situation with experienced prosthetic users and a lab setting. We expect that the control of prostheses in daily life is even more difficult

**Table 3**

Mean (SD) for movement time and index of harmonicity (H) for both types of prostheses.

TD	ID	MT		H	
		Forearm	Upper arm	Forearm	Upper arm
5	3	422 (.16)	432 (.17)	.38 (.35)	.51 (.31)
	4	546 (.20)	544 (.18)	.35 (.26)	.23 (.18)
	5	801 (.28)	888 (.20)	.03 (.03)	.04 (.05)
10	3	391 (.03)	441 (.09)	.72 (.09)	.62 (.26)
	4	474 (.20)	620 (.13)	.52 (.42)	.21 (.14)
	5	789 (.20)	808 (.15)	.06 (.07)	.08 (.06)
20	3	422 (.02)	472 (.03)	.83 (.07)	.74 (.15)
	4	550 (.13)	643 (.13)	.52 (.27)	.40 (.29)
	5	808 (.23)	878 (.15)	.18 (.14)	.06 (.03)
30	3	397 (.08)	612 (.21)	.90 (.06)	.60 (.37)
	4	806 (.39)	751 (.29)	.48 (.39)	.43 (.50)
	5	670 (.19)	941 (.20)	.48 (.34)	.12 (.10)

TD = target distance (cm) ; ID = index of difficulty; MT = movement time (ms); H = index of harmonicity.

because of influences from the environment and the need to perform double tasks.

## 5. Conclusions

By characterizing movements with upper extremity prostheses, specific deviations have been pinpointed between two types of prostheses and between prostheses and existing knowledge of able-bodied behavior. Developments in technology and rehabilitation should focus on these issues to increase the use of prostheses, in particular on improving motor characteristics and the control of the elbow, and learning to coordinate the reach and the grasp component in prehension.

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